Kinetic changes during a six week minimal footwear and gait-retraining intervention in runners.

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ABSTRACT

An evaluation of a 6-week Combined minimal footwear transition and gait-retraining combination vs gait retraining only on impact characteristics and leg stiffness. Twenty-four trained male runners were randomly assigned to either; 1) Minimalist footwear transition Combined with gait-retraining over a 6 week period ("Combined" group; n=12) examined in both footwear, and 2) a gait-retraining group only with no minimalist footwear exposure ("Control"; n=12). Participants were assessed for loading rate, impact peak, vertical, knee and ankle stiffness, and foot-strike using 3D and kinetic analysis. Loading rate was significantly higher in the Combined group in minimal shoes at pre-tests compared to a Control ($p \leq 0.001$), reduced significantly in the Combined group over time ($p \leq 0.001$), and was not different to the Control group at post-tests ($p=0.16$). The impact peak ($p=0.056$) and ankle stiffness reduced in both groups ($p=0.006$). Loading rate and vertical stiffness was higher in minimalist footwear than conventional running shoes both pre ($p \leq 0.001$) and post ($p=0.046$) the intervention. There has a higher tendency to non-rearfoot strike in both interventions, but more acute changes in the minimalist footwear. A Combined intervention can potentially reduce impact variables. However, higher loading rate initially in minimalist footwear may increase the risk of injury in this condition.

Key Words: Minimalism, running footwear, running related injury, barefoot running, running technique.

Word Count: 4400

INTRODUCTION:

Running is a popular exercise modality of which participation has increased over the last number of years; for example the running population has grown 10% since 2010 in the USA and now has a total of 35.5million participants (Rothschild, 2012b). However, the incidence of lower extremity injuries experienced by runners today remains exceptionally high (19.4 to 79.3%) (van Gent et al, 2007). As a result, many strategies have been adopted by runners to reduce injury risk.

One strategy is the use of minimalist footwear. Minimalist footwear are shoes with a smaller mass, greater sole flexibility, a lower profile, and lower heel-to-toe drop than conventional running shoes (Lussiana, Hérbert-Losier & Mourot, 2015). Runners in this footwear type have been found to be more likely to adopt a non-rearfoot strike pattern (Altman & Davis, 2012; Giandolini et al, 2013), and a non-rearfoot strike pattern has been found to reduce impact forces (Altman & Davis, 2012; Cheung & Rainbow, 2014; Lieberman et al, 2010). Impact characteristics of the vertical ground reaction force such as the loading rate and the impact peak have been associated with increased injury risk in runners for injuries such as stress fractures (Pohl et al, 2008;Milner, Ferber, Pollard, Hamill, & Davis, 2006), and plantar fasciitis (Pohl, Hamill & Davis, 2009). However, an important consideration with regard to minimalist footwear use is that some runners do not adopt a non-rearfoot strike pattern despite the reduction in cushioning properties of the shoe (Willson et al, 2014). A non-rearfoot strike may result in higher loading rate (De Wit, De Clerq, & Aerts, 2000; Divert, Mornieux, Baur, & Mayer, 2005b) given that these minimalist footwear do not have any heel cushioning to attenuate this impact (De Wit et al, 2000; Lieberman et al, 2010). The change in runner's foot striking patterns may be a reason that higher impact related injuries such as stress fractures have been observed during a minimalist footwear transition (Ryan, Elashi, Newham-West, & Taunton, 2013; Salzler, Bluman, Noonan, Chiodo, & Richard, 2012). Therefore, it may be beneficial to include "barefoot inspired" gait-retraining when transitioning to minimalist footwear, to increase the likelihood that runners adopt a non-rearfoot strike pattern. Indeed gait-retraining for runners is increasing in popularity for this reason (Goss & Gross, 2012).

Gait-retraining has been prescribed as a means to promote a more "natural" running gait that is theorised from barefoot movement, both in the literature (e.g. Giandolini et al, 2013; Goss & Gross, 2013), and from footwear manufacturers (e.g. http://www.merrell.com/US/en/MConnect_Learn). In addition to promoting a non-rearfoot strike pattern, this popular gait-retraining also advocates increases in stride frequency, lighter steps, and a more upright posture during running (e.g. "Chi" or "Pose" running) (Dallam, Wilber, Jadelis, Fletcher & Romanov, 2005; Fletcher, Bartlett, Romanov & Fotouhi, 2008; Goss & Gross, 2012). Elements of this gait-retraining have been found to reduce loading rate and impact peak, via increases in stride frequency and adopting a non-rearfoot strike pattern (Altman & Davis, 2012; Crowell & Davis, 2011; Goss & Gross, 2012). However, the area of gait-retraining and injury prevention is still limited in the literature and demands more attention.

It may therefore be beneficial to combine both the minimalist footwear and gait-retraining intervention, because if some runners do not adopt a non-rearfoot strike pattern in minimalist footwear (e.g. Willson et al, 2014), then gait-retraining could be of benefit to increase the likelihood of this change. Likewise, runners undergoing gait-retraining may benefit from minimalist footwear use, since some authors have suggested that conventional running shoes may reduce the runner's ability to non-rearfoot strike pattern and increase stride frequency due to shoe design and sensory "insulation" (De Wit et al, 2000; Lieberman et al, 2010;

Robins & Hanna, 1987). A combination of minimal footwear and gait-retraining has yet to be examined, and of particular interest are kinetic and kinematic parameters associated with injury over this "transition" period. These include loading rate (Coyles, Lake & Lees, 2001; Milner et al, 2006; Pohl et al, 2009), the impact peak (Hreljac, Marshall & Hume, 2000), foot strike patterns (Lieberman et al, 2010), and leg stiffness characteristics (McMahon, Comfort & Pearson, 2012), since any increase in stiffness will result in increased loading rate and impact peak due to a less compliant structure in the first period of stance (Butler, Crowell & Davis, 2003).

The primary aim of this study is therefore to investigate the effects of a 6 week Combined minimalist footwear and gait-retraining (Combined) intervention on factors associated with increased risk of injury (impact peak, loading rate, vertical and joint stiffness, foot strike pattern) during running, when compared to a Control who had no minimalist footwear exposure, and 2) to directly compare minimalist footwear vs. conventional running shoes on these injury related variables, pre and post a transition period in the Combined group. We hypothesize that a 6 week Combined intervention will result in significantly lower values in minimalist shoes for factors associated with injury when compared to only gait retraining in conventional running shoes in the Control group. Secondly, we hypothesize that there will be no difference in loading variables, but higher vertical stiffness, in the minimalist footwear condition when compared to conventional running shoes in the Combined group.

METHODS

PARTICIPANTS: Forty trained male runners were recruited from local athletic clubs via internet advertising. Inclusion criteria: Running 5 to 7 days per week for a minimum of 40km/week regularly competing at 5km to marathon distances, and a club level of participation. Participants were excluded if they had reported any lower limb injuries in the last three months, or had previous barefoot or minimalist running experience. Only male athletes were used to eliminate gender differences in running mechanics (Ferber, Davis & Williams, 2003). The participants gave informed consent and ethical approval for this study was granted by the Dublin City University Ethics Committee.

EXPERIMENTAL DESIGN: Using a parallel randomised Control design, two groups of 14 participants were randomly (random number draw) established after screening for inclusion/exclusion criteria (Figure 1). The first group was tested in both minimalist footwear and conventional running shoes at pre-test and post-tests, and were required to gradually increase exposure to minimalist footwear as well as incorporate gait-retraining into their running over this six week period ("Combined" group). The second group (Control) were only tested in conventional running shoes at pre and post tests, but also included the gait-retraining. The Control group was required to train as normal, and had absolutely no exposure to minimalist footwear at any point. To balance order effects in the Combined group, a Latin square design was used to determine which footwear condition (minimalist footwear or conventional running shoes) was tested first between the pre and post tests. On the first visit, foot size was measured and participants in the Combined group were provided with one pair of minimalist footwear (Vibram® Five Finger "KSO"; ~150 g/pair), and all participants were provided with a pair of neutral conventional running shoes (Asics® "GEL-Cumulus" 2012; ~400g/pair).

TESTING PROCEDURE: A 12 camera motion analysis system (Vicon 512 M, Oxford Metrics Ltd, England) was used to record the position of six reflective markers (250Hz). Reflective markers were attached unilaterally (right side), using double sided tape on the following anatomical landmarks; distal head of the fifth metatarsal bone, posterior heel (level of calcaneus at the most posterior apex of the shoe), lateral malleolus, lateral epicondyle of the femur, greater trochanter, and the acromion process (Figure 2). One force plate (BP-600900, AMTI, MA, USA) recorded the ground reaction forces (1000Hz). Before overground tests, participants were required to run on a treadmill for four minutes at 11km/h, as four minutes has been suggested to optimise leg stiffness and running technique depending on surface and shoe hardness (Divert, Baur, Mornieux, Mayer & Belli, 2005a). This strategy was employed to prevent any “carry-over” of neuromuscular strategies from one type of footwear to another. Over ground runs were performed using 5 separate, successful right foot contacts with the force plate, where the starting position was changed to ensure full contact with the covered force plate, and with no mention of its presence to avoid targeting issues. The runway was 25m in length. Successful contact was monitored on screen via 3D markers in relation to the location of the force plate. Participants were not informed of measured parameters as this has been found to influence gait (Morin, Samozino & Peyrot, 2009). Speed was monitored during trials and feedback provided to ensure that participants ran at 11km/h (3.05m/s) using speed gates, 20m apart and using calculated average velocity (Brower Timing Systems, CM L5 MEM, Salt Lake City, Utah, USA) with a 5% acceptable variance. The Control group underwent the same procedure but only tested in conventional running shoes. Foot strike pattern distribution was ascertained from treadmill running prior to the four minute warm up period using Pedar X sensory insoles (Novel Pedar X, Munich, Germany) as part of a wider study with these participants. Foot strike patterns were identified using the foot strike index (Altman & Davis, 2012), where the plantar surface was divided into thirds (heel, midfoot, forefoot), and the foot strike pattern was identified by the location of the centre of pressure at its initial contact point, averaged over 60 seconds of steps. The distribution of foot strike patterns is represented as frequencies.

INTERVENTION: Immediately after pre-tests, each participant in the Combined group was provided with a structured progression of minimalist footwear use over the six week familiarisation period and relevant injury prevention exercises (Rothschild, 2012b; Tenforde et al, 2011) (Table 2). The gait-retraining was provided to all participants and is based on current findings in the literature, these changes have also become the main kinematic changes promoted in the running gait-retraining marketplace (Dallam et al, 2005; Fletcher et al, 2008; Goss & Gross, 2013). Both the gait-retraining and exercises were fully demonstrated during a 30 minute session until changes to stride frequency (+10%), a forefoot strike pattern, more upright posture and a softer landing were adopted by the participants. It was required that the minimalist footwear training took place at the beginning of any training session, and then participants were allowed to continue their normal training load in their own preferred conventional running shoes, thus not reducing their overall training workload. The participants were asked to work on the gait-retraining changes both in minimalist footwear and conventional running shoes, gradually incorporating it into longer runs. The Control group received no minimalist footwear intervention, and were asked to remain in their own regular conventional running shoes for the duration of the testing, whilst undertaking identical gait-retraining changes and the injury prevention exercises. Compliance to the intervention was recorded in diaries by participants and examined for completion at post-tests.

DATA PROCESSING: The marker data was filtered using a recursive second order low pass Butterworth digital filter (Winter, 2009). The marker set and force plate data were filtered using a 9Hz and 50Hz cut off frequency, respectfully. An inverse dynamics approach investigating the sagittal plane only was adopted using anthropometric data from Winter (2009) with a custom code written in Matlab software package (R2012a, MathWorks

Inc., USA). Knee stiffness was calculated as K=Δjoint moment/Δjoint angle from initial contact to midstance (50% of the stance phase) (Hamill, Gruber & Derrick, 2014). In Hamill et al (2014), ankle stiffness was calculated in the same manner. However, since the ankle is very likely to both plantarflex and then dorsiflex with a rearfoot strike pattern during the first half of stance, this method of comparing foot strike patterns may overestimate ankle stiffness during a rearfoot strike, since the Δjoint angle calculation does not take into account the change in direction. In contrast, a forefoot strike pattern will only experience dorsiflexion in the first half of stance and thus this Δjoint angle will be higher. Therefore, we calculated Δjoint angle from the point in which the ankle began to dorsiflex until midstance, irrespective of the foot strike adopted. Vertical stiffness was calculated as K=F/ΔL, where F is equal to the peak vertical component of the ground reaction force, and ΔL is the change in displacement of the centre of mass (Butler et al, 2003). The centre of mass was determined based on the marker data and centre of segments as described in Winter (2009). The impact peak was determined using the ground reaction force data normalised to body weight and visually identifying the first impact peak. In the case that this peak was absent, a representative value of 13% of stance was used (Samaan, Rainbow & Davis, 2014; Willy, Pohl & Davis, 2008; Blackmore, Willy & Creaby, 2016). Loading rate was calculated as the slope of the line from 20-80% of the impact peak (normalised to body weight). Again in the case where no impact peak was apparent, a substituted value of the slope of the line from 2-10% of stance was adopted (Samaan, Rainbow & Davis, 2014).

DATA ANALYSIS: Aim 1: Differences between the Combined group (minimalist shoes) and Control group (conventional shoes) were examined with a two-way mixed ANOVA for within-subject (difference between pre and post intervention – "time") and between-subject (differences between groups – "group") effects, as well as any interactions. Secondly, in order to examine aim 2 (difference between minimal footwear and conventional running shoes in the Combined group "condition"), the differences in footwear condition were examined using a repeated measures ANOVA for within-subjects effects. Specific differences at pre and post tests were examined using post-hoc tests, and any interactions were also explored in this fashion (Statistical Package for the Social Sciences data analysis software V16.0, SPSS Inc., Chicago, Illinois, USA). Statistical significance was accepted at $\alpha \leq 0.05$. Effect sizes are reported as partial eta squared (ηp^2). The effect was expressed as 95% confidence limits (mean change [lower to upper confidence interval of the difference]) (Batterham & Hopkins, 2006). The interpretation of results took into account a combination of the 95% confidence interval of the difference (likelihood of an effect being different than zero), the effect size, and the p value. Therefore, some values that are "approaching significance" are also discussed, given recent controversy over using p values alone for interpretation of statistical tests (E.g. Greenland et al, 2016). Foot strikes have simply been presented as frequencies.

RESULTS:

With respect to injuries and dropout experienced during the intervention, two Combined participants became injured (hamstring and gastrocnemius issues), and two Control group participants did not return for subsequent testing with no reason provided (remaining n=24; intervention n=12; Control n=12). Anthropometric and descriptive data for the final n can be observed in Table 1. Seven Combined and one Control group participants reported triceps surea soreness, with three of these cases being severe resulting in a temporary reduction in running mileage for several days.

Participant compliance with the intervention schedule was established using the training diaries and expressed as a percentage of total completion for both the exercises and the minimalist footwear transition. The Combined group completed (mean [range]) 87% [56 to 96% of the injury prevention exercises, and 96% [88 to 100%] of the minimalist footwear intervention; the Control group completed 92% [84 to 98%] of the injury prevention programme.

The mean ± SD for all variables are presented in Table 3, in addition, the results of all statistics tests for aim 1 can be observed in Table 4. With respect to the first study aim, we observed a significant interaction effect between time*group for loading rate ($p=0.034$). When we examined this interaction with post-hoc tests, loading rate was observed to be 36% higher in the Combined group vs. Control group at pre-tests ($p \leq 0.001$, mean diff: 35.14 $BW \bullet s^{-1}$ [15.74 to 54.54]), but this difference was reduced to 23% at post-tests and was non-significant ($p=0.16$, mean diff: 14.79 $BW \bullet s^{-1}$ [-6.09 to 35.66]). This was due to a significant 33% reduction in loading rate in the Combined group from pre to post-tests ($p \leq 0.001$; mean reduction: -31.67 $BW \bullet s^{-1}$ [-47.56 to -15.78]) that did not occur to the same magnitude (18% reduction) in the Control group ($p=0.08$, mean reduction: -11.32 $BW \bullet s^{-1}$ [-24.26 to 1.62]). There was no significant main effect for group in the impact peak ($p=0.59$), vertical stiffness ($p=0.61$), or ankle stiffness ($p=0.38$), however there was a significant main effect for differences between groups in knee stiffness ($p=0.034$). This was not specific to any time point (pre $p=0.13$, post $p=0.07$), but indicated a 21% lower knee stiffness in the Combined group throughout testing.

The only variable other than loading rate to indicate a significant main effect for time (change from pre to post) was ankle stiffness, which indicated an 12% reduction in ankle stiffness in both groups (Combined p=0.05, Control p=0.03). We also note that the reduction in the impact peak was a worthwhile 10% (we calculated a smallest worthwhile clinical effect of 4% [0.2xbetween-subjects SD of the pre-tests]) from pre to post tests (p=0.056; ηp^2=0.16; 95% CI [-0.33 to 0.004]). This was a 14% reduction in the impact peak in the Combined group from pre to post tests, but only a 7% reduction in the Control group.

After the intervention, there was a higher tendency for participants both in the Combined (+2 participants) and Control group (+5 participants) to adopt a non-rearfoot strike (Figure 3). Note that the amount of initial non-rearfoot strikers was already greater in the Combined group in minimal footwear due to a footwear effect.

Statistical results for the second aim can be observed in table 5. When examining the difference between minimal footwear and conventional running shoes in the Combined group, there was an interaction effect between condition*time for loading rate. Post-hoc tests revealed that loading rate was observed to be 73% higher in the minimalist footwear condition compared to conventional running shoes at pre-tests (p≤0.001, mean diff: -40.457 BW•s^{-1} [-54.46 to -26.45]), but this difference was reduced to 35% at post-tests (p=0.046, mean diff: -16.81 BW•s^{-1} [-33.3 to -0.32]). This was due to a significant 33% reduction in loading rate in the minimalist footwear condition from pre to post-tests (p=0.001; mean reduction: -31.67 BW•s^{-1} [-47.56 to -15.78]) that did not occur to the same magnitude (14.4% reduction) in conventional running shoes (p=0.08, mean reduction: -8.02 BW•s^{-1} [-17.15 to 1.1]. Other main effects for condition identified a significantly higher vertical stiffness in minimal footwear when compared to conventional running shoes (p=0.002). There was no significant main condition effect for impact peak (p=0.43), or ankle stiffness (p=0.26) between footwear types. However whilst no main effect was observed for knee stiffness (p=0.09), the minimal footwear condition was significantly lower than conventional running shoes at post-tests (p=0.05) when examine post-hoc tests. Both before and after the intervention, there was a higher prevalence of non-rearfoot strikes in the minimal footwear observed compared to conventional shoes in the Combined group (Figure 3).

DISCUSSION:

The main finding of the present study was a significant reduction in loading rate in the Combined group as a result of a six week minimalist footwear and gait-retraining intervention. This change over time was not observed in the Control group and therefore supports our study hypothesis. This has not been measured during a familiarisation period with gait-retraining previously in the literature. We observed a significant 33% reduction in loading rate in the Combined group, and a non-significant 18% reduction in the Control group. However, loading rate was observed to be significantly higher at pre-tests in the Combined group in minimalist footwear.

One possible explanation for the greater reduction in loading rate in the minimalist footwear condition associated with the Combined intervention may be a result of necessary impact attenuation tactics to counteract the higher loading rate when in minimalist footwear compared to the cushioned surface in conventional running shoes. This could be considered a positive improvement in the running gait, as increased loading rate has been linked to injury in numerous studies (Coyles, Lake & Lees, 2001; Milner et al, 2006; Pohl et al, 2009). However, loading rate was still significantly higher in minimalist footwear (Combined group) than conventional running shoes (Control group, and conventional shoes in the Combined group) at pre-tests and therefore it may be dangerous to utilise minimalist footwear for reducing factors associated with injury initially. A higher loading rate has been observed previously in different minimalist footwear when directly compared to conventional running shoes (Paquette, Zhang & Baumgartner, 2013; Sinclair, Greenhalgh, Brooks, Edmundson & Hobbs, 2013; Willy & Davis, 2014) that may be due to a reduction in the cushioning properties of minimalist footwear that reduce the time over which the impact occurs (Lieberman et al, 2010). This may predispose novice minimalist footwear runners to injuries associated with higher loading rate such as tibial and metatarsal stress fractures (e.g. Ridge et al, 2013; Salzler et al, 2012). A further consideration however is that the post-test values were not different between groups, suggesting that runners familiarised to minimalist footwear do not exhibit any difference in loading rate than conventionally shod runners. This is likely as a result of the tendency to adopt a non-rearfoot strike pattern as observed post-tests (Willson et al, 2014).

The observation that the Control group in the present study did not significantly reduce loading rate to the same degree is surprising, as using gait-retraining has been observed elsewhere to reduce loading rate and has been associated with the adoption of a non-rearfoot strike pattern (Altman & Davis, 2012; Crowell & Davis, 2011; Giandolini et al, 2013; Goss & Gross, 2012), although an 18% reduction was observed. Therefore the use of gait-retraining in conventional running shoes may be a safe and effective way to slightly reduce loading rate but not to the same degree as a Combined intervention with minimal footwear.

With respect to the impact peak, whilst the main effect for time was non-significant (p=0.056), the magnitude of the reduction was noteworthy and above a calculated smallest clinical effect. As with the loading rate, there appeared to be a greater reduction in the impact peak in the Combined group, and the impact peak has also been linked to injury in previous studies (Hreljac, Marshall & Hume, 2000). Therefore, if the focus of a training intervention was to reduce impact peak, a Combined intervention may be more effective than a Control intervention. A larger sample size may have benefited this observation.

When examining the difference between the Combined and Control groups with regard to ankle and knee stiffness, there was no difference in ankle stiffness between groups, but a lower knee stiffness in the Combined group throughout testing (21%). This reduction in knee stiffness suggests reduced knee moments or increased knee excursion in the minimalist footwear condition compared to conventional running shoes. This is supported by Coyles et al (2001) who observed a reduction in knee stiffness when barefoot compared to conventional running shoes, but no other research has investigated joint stiffness differences between minimalist footwear and conventional running shoes to the best of our knowledge. The lack of any difference between minimal footwear and conventional shoes for ankle stiffness has been previously established, although a lower value was observed barefoot in this study (Chambon, Delattre, Guéguen, Berton & Rao, 2014). This suggests that the present minimalist footwear may not provide enough sensory feedback to elicit any difference in ankle stiffness for impact attenuation (Robbins & Hanna, 1987), but the barefoot condition may (Chambon et al, 2014). However, we did note a significant decrease in ankle stiffness in both the Combined and Control groups over time, suggesting that the gait retraining element may be responsible for this change. Whilst previous methods for calculating ankle stiffness may be different (see methods), our results are supported by both Arampatzis et al (2001) and Hamill, Gruber & Derrick (2012) which suggest a reduction in ankle stiffness with a more anterior foot strike. This may be important for understanding injury risk, as low stiffness values have been suggested to increased risk of soft tissue injuries, whereas high leg stiffness may be linked to bone-related injuries (McMahon et al, 2012).

With regard to the second study aim, we observed significantly higher loading rate in minimalist footwear compared to conventional running shoes both pre (73%) and post (35%) the transition period, this is a very similar finding to the initial comparison between the Combined and Control group, and the same implications apply. With respect to the impact peak, previous research has been equivocal, with some studies observing either a higher (Willy et al, 2008), lower (Squadrone & Gallozzi, 2009), or equal impact peak (Paquette et al, 2013; Sinclair et al, 2013) in minimalist footwear compared to conventional running shoes. Therefore the current research supports the latter findings in that there is no significant difference in impact peak between minimalist footwear and conventional running shoes. However, it must be noted that the Combined group did experience more muscle soreness and triceps surae pain than the Control group, indicating higher or novel musculoskeletal work as a result of the intervention in the Combined group. Finally, a higher vertical stiffness in minimal footwear may likely be due to a reduction in vertical oscillation and increased stride frequency observed in minimal shoes (Lussiana et al, 2015), although the Lussiana et al (2015) study did not observe a difference in vertical stiffness that contrasts our results. However, this finding may also be due to deformation of the convention running shoe reducing stiffness in this footwear type (Divert et al, 2005a). This factor remains to be examined further with respect to injury risk and footwear.

This study is not without limitations; the method of substituting an arbitrary time of stance for the impact peak when absent requires further validation. The results may also only apply to trained males and so examination of these effects in females and untrained runners is warranted. We also did not control the amount of gait retraining adopted by participants gradually throughout the programme which may be dangerous and may partly explain the injuries experienced in this study. Finally, given the lack of a-priori power analysis, out study may be underpowered to detect some important effects.

The adoption of a minimalist footwear and gait-retraining Combined intervention may be beneficial for the reduction of the loading rate and potentially the impact peak over a six week period. However, this can result in significantly higher loading rate in the minimalist footwear condition compared to conventional running shoes initially that may increase the risk of injury in the minimalist footwear condition. Therefore if the aim of a training intervention was to reduce loading rate, care has to be taken in the early stages of the transition. It appears that neither a Combined intervention has an acute effect on knee stiffness, likely as a footwear effect, and a gait-retraining intervention can reduce ankle stiffness. When comparing minimalist footwear to conventional running shoes, we observed a higher vertical stiffness in the minimalist footwear condition. Irrespective of these differences in stiffness, the impact peak was not different between conventional running shoes and minimalist footwear and the loading rate was significantly higher in minimalist footwear throughout testing.

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FIGURE CAPTIONS:

Figure 1. Flow diagram of the progress through the parallel study design for each group.

Figure 2. Anatomical location of 3D markers in the sagittal plane.

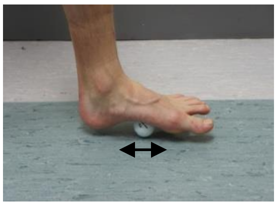
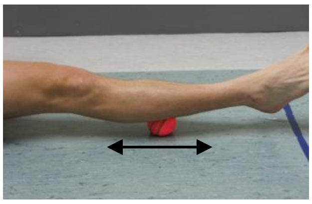
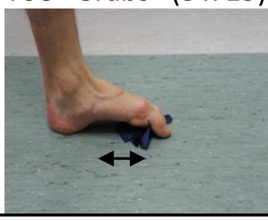
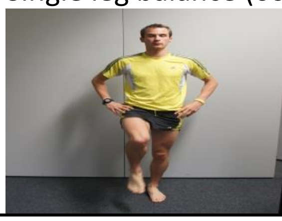
Figure 3. Foot strike pattern changes represented by the number of participants adopting each foot strike pattern pre and post the 6 week intervention, in A) the Combined group (conventional running shoes and minimalist footwear), and B) the Control group (conventional running shoes only).

Table 1. Anthropometric and descriptive data (Mean [± SD]) for the Combined and Control groups. P values represent difference between groups established with an independent t test.

	Age (years)	**Stature (cm)**	**Body mass (kg)**	**$\dot{V}O_{2max}$ ($ml \cdot kg \cdot min^{-1}$)**	**kilometers per week (km)**
Combined (n=12)	36 (±7)	179 (±4.6)	78.8 (±10.2)	60.94 (±7.36)	64 (±20)
Control (n=12)	34 (±9)	180.2 (±5.4)	79.7 (±9.2)	60.56 (±8.08)	60 (±14)
Difference test	P=0.11	P=0.79	P=0.65	P=0.15	P=0.46

Table 2. Six week familiarization to minimal footwear including gait-retraining guidelines and simple exercises for injury prevention.

Week	Minimal Footwear Training Programme
Week 1	Throughout: Wearing minimal shoes and going barefoot as much as possible in normal daily routines 3 days: 5 -8 mins easy running on the spot or in corridors/garden at home 3 days: Prescribed exercises*
Week 2	3 days: 10 – 15 mins running on grass, 3 minutes on pavement 3 days: Prescribed exercises*
Week 3	2 days: 20 mins running on grass, 5 - 8 minutes on pavement 1 day: 25 mins running on grass 3 days: Prescribed exercises*
Week 4	2 days: 25 mins on grass, 10 mins on pavement 1day: 30 mins on grass 2 days: Prescribed exercises*
Week 5 + 6	2-3 days: 30 mins on grass, 15 mins on pavement 1day: 40 mins on grass 2 days: Prescribed exercises*

Gait-retraining guidelines	Injury prevention (10 minutes)	
Keep stride short and increased cadence Run as light and quiet as possible	Plantar Fascia and Triceps Surae Rolling x 5 mins 	
Land on the forefoot, allowing heel to contact Immediately afterwards	Ankle Mobility (3 x 15) 	Calf Raises (3 x 15) 
Keep hips forward and head up, running as tall and proud as possible (Dallam et al, 2005; Fletcher et al, 2008; Goss & Gross, 2013)	Toe “Grabs” (3 x 15) 	Single leg balance (60secs) 

* No specification was made as to whether the exercises were completed on the same days as the running intervention or not.

Table 5. Mean difference data, 95% confidence intervals and effect sizes for main effects between **conditions** (minimal footwear vs. conventional running shoe) in the Combined group.

Combined group (n=12)	Analysis	Mean difference	95% confidence levels		P value	Effect size
	F tests		Lower	Upper		ηp^2
Loading rate **($BW \cdot s^{-1}$)**	Condition	28.635	14.77	42.5	0.001*	0.68
	Time*Condition				0.002*	0.63
Impact peak (BW)	Condition	0.06	-0.21	0.09	0.43	0.06
	Time*Condition				0.28	0.12
Vertical stiffness ($n \cdot m^{-1}$)	Condition	3231.34	1543.68	4919.01	0.002*	0.68
	Time*Condition				0.62	0.03
Knee Stiffness ($n \cdot m \cdot deg^{-1}$)	Condition	-0.44	-0.97	0.09	0.09	0.26
	Time*Condition				0.08	0.28
Ankle Stiffness ($n \cdot m \cdot deg^{-1}$)	Condition	-0.72	-2.98	1.55	0.49	0.05
	Time*Condition				0.34	0.09

For time effects, minus represents a reduction at post-tests. For condition effects, minus represents a lower value in minimal footwear. $^{*}p \leq .05$

Table 4. Mean difference data, 95% confidence intervals and effect sizes for main effects over **time** (pre to post-tests) and between **groups** (Combined [minimal footwear] vs. Control [conventional running shoe]).

Combined vs. Control group (n=12)	Analysis	Mean difference	95% confidence levels		P value	Effect size
	F tests		Lower	Upper		ηp^2
Loading rate **($BW \cdot s^{-1}$)**	Time	-21.49	-30.85	-12.14	0.001*	0.52
	Group	24.94	7.11	42.81	0.008*	0.29
	Time*Group				0.034*	0.20
Impact peak (BW)	Time	-0.17	-0.33	0.004	0.056	0.16
	Group	-0.07	-0.32	0.19	0.59	0.01
	Time*Group				0.47	0.03
Vertical stiffness ($n \cdot m^{-1}$)	Time	1742.64	-487.80	3973.08	0.12	0.11
	Group	997.25	-2955.31	4949.81	0.61	0.01
	Time*Group				0.50	0.02
Knee Stiffness ($n \cdot m \cdot deg^{-1}$)	Time	-0.37	-1.33	0.59	0.44	0.03
	Group	-1.27	-2.43	-0.11	0.034*	0.20
	Time*Group				0.83	0.002
Ankle Stiffness ($n \cdot m \cdot deg^{-1}$)	Time	-1.18	-1.98	-0.37	0.006*	0.31
	Group	1.22	-1.64	4.09	0.38	0.04
	Time*Group				0.87	0.001

For time effects, minus represents a reduction at post-tests. For group effects, minus represents a lower value in Combined group. $^{*}p \leq .05$

Table 3. Mean ± SD for all variables in the study for both the Combined and Control groups.

Combined group (n=12)		**Pre**	**Post**
Loading rate **($BW \cdot s^{-1}$)**	Conventional	55.56 ± 18.84*$^{\psi}$	47.54 ± 16.46*
	Minimalist	96.02 ± 28.01	64.35 ± 32.41$^{¥}$
Impact peak (BW)	Conventional	1.43 ± 0.36	1.39 ± 0.42
	Minimalist	1.58 ± 0.26	1.35 ± 0.42
Vertical stiffness **($n \cdot m^{-1}$)**	Conventional	31246.16 ± 3568.69	31569.62 ± 3508.29*
	Minimalist	34040.11 ± 6009.41	35238.35 ± 3865.49
Knee Stiffness **($n \cdot m \cdot deg^{-1}$)**	Conventional	6.2 ± 1.7	6.99 ± 1.94*
	Minimalist	6.39 ± 1.71	5.92 ± 1.66
Ankle Stiffness **($n \cdot m \cdot deg^{-1}$)**	Conventional	10.73 ± 5.63	10.91 ± 5.31
	Minimalist	10.66 ± 4.78	9.55 ± 3.71
Control group (n=12)			
Loading rate **($BW \cdot s^{-1}$)**	Conventional	60.88 ± 15.51	49.56 ± 12.21
Impact peak (BW)	Conventional	1.58 ± 0.3	1.48 ± 0.4
Vertical stiffness **($n \cdot m^{-1}$)**	Conventional	32548.33 ± 6038.81	35024.39 ± 5052.69
Knee Stiffness **($n \cdot m \cdot deg^{-1}$)**	Conventional	7.56 ± 1.81	7.29 ± 1.76
Ankle Stiffness **($n \cdot m \cdot deg^{-1}$)**	Conventional	9.5 ± 2.82	8.26± 1.89 $^{¥}$

* = significant difference between footwear at time point. ¥ = significant difference from pre to post tests. ψ= significant difference between combined (minimal footwear) and control (conventional running shoes) at time point. $P \leq 0.05$.

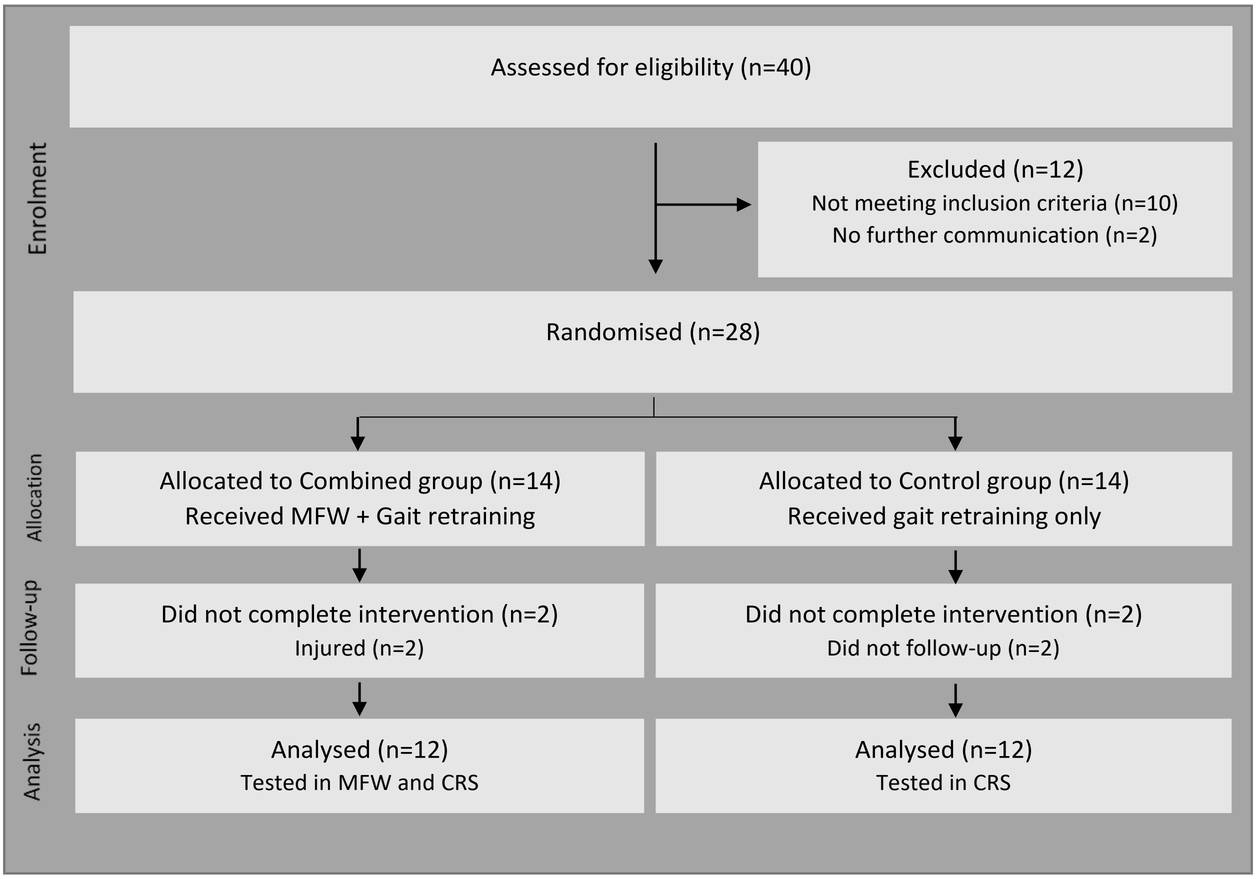


Figure 1. Flow diagram of the progress through the parallel study design for each group. MFW = minimal footwear, CRS = conventional running shoes.

Figure 2. Anatomical location of 3D markers in the sagittal plane.

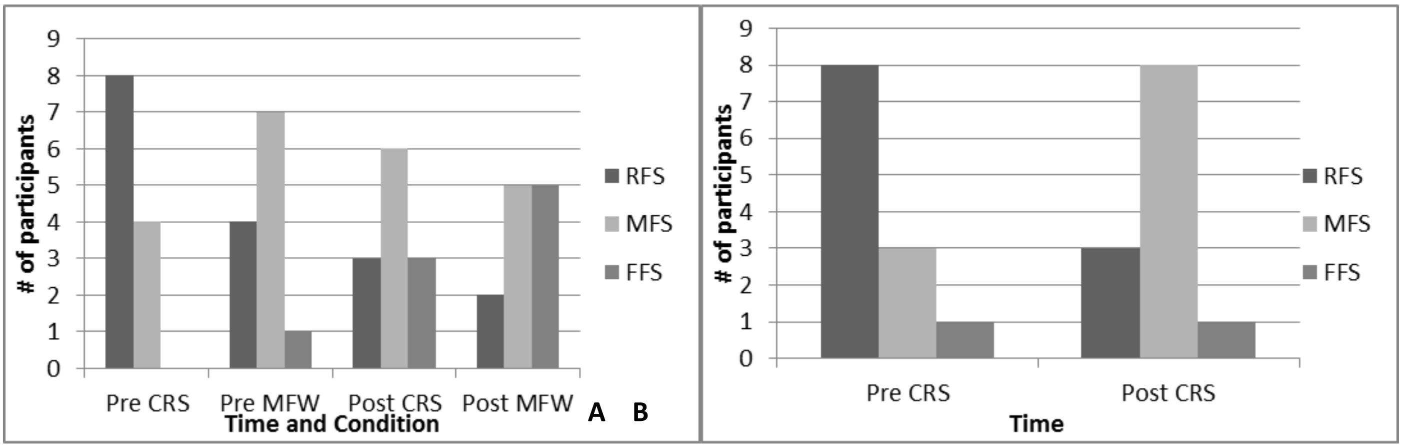


Figure 3. Foot strike pattern changes represented by the number of participants adopting each foot strike pattern pre and post the 6 week intervention, in A) the Combined group (conventional running shoe [CRS] and minimalist footwear [MFW]), and B) the Control group (conventional running shoe [CRS] only).